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16. ABSTRACT

In this study of oxygen transfer using fine-bubble diffusers in the presence of wastewater contaminants and surfactants, an experimental method and mathematical models were developed that can handle rapidly changing water quality under process conditions. The models were verified experimentally with tap water containing surfactants and activated-sludge mixed liquor. The pilot-scale aeration column with full-scale liquid depth under operating condition could be used to simulate the full-scale aeration tank. The variation of alpha factor in the mixed liquor can be explained by a readily measured variable, microbial oxygen uptake.

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JOURNAL ARTICLE

Evaluation of fine-bubble alpha factors in near full-scale equipment

H. J. Hwang, M. K. Stenstrom

The activated sludge process is currently the most popular method of secondary biological wastewater treatment, and its popularity is increasing. Aeration is the most energy intensive aspect of plant operation and can consume as much as 60 to 80% of the total energy requirements in a modern wastewater treatment plant.[1] As power costs increase, many plant owners and operators are replacing older, less efficient aeration systems such as coarse-bubble, spiral-roll diffusers, with more energy-efficient systems such as fine-bubble, full-floor coverage systems.[1-4]

Unfortunately, the phenomena underlying aeration processes have not been fully understood. Oxygen transfer rate from gas to liquid phase depends on such factors as aeration method, power input intensity, mixing intensity or turbulence, temperature, test facility geometry, and physicochemical properties of the liquid. Therefore, design engineers must anticipate the effects of varying liquid properties.

Aeration devices are conventionally evaluated in clean water, and the results are adjusted to process operating conditions through widely used conversion factors (alpha, beta, and theta) and nondimensional scale-up methods. The inherent-problem in this approach is that these factors depend on operating conditions and water quality.[5] The alpha factor is especially sensitive to trace contaminants, particularly surfactants. This paper presents a practical method of measuring alpha factors for fine-bubble diffusers under rapidly changing conditions of water quality.

FACTORS AFFECTING MASS TRANSFER RATE

Air flow rate. Different effects of air flow rate on mass transfer rate have been reported. Some studies show the volumetric mass transfer coefficient (K_La) increases almost linearly with air flow rates.[3,6-10] Because most diffusers produce larger bubbles at a higher air flow rate, the ratio of bubble surface area to volume decreases per unit air flow rate. To obtain a linear relationship, something else must compensate, such as an increase in liquid film coefficient. Others do not report a linear relationship of K_La and air flow rate. Jackson and Shen[11] and Jackson and Hoech[12] related K_La value to the power of superficial air velocity, and found that the exponent varied from 1.08 to 1.13. With bench-scale experimental facilities, King[13,14] showed that the rate of oxygen absorption varied from 0.825 to 0.86 power of air flow rate depending on liquid depth and geometry.

Liquid depth. Because of different surface renewal properties that occur when bubbles form, rise, and burst at the surface, the value of the mass transfer coefficient is affected by liquid depth. Generally, it decreases with increasing liquid depth above a submerged diffuser.[15-17] However, Downing *et al.*[18] reported increasing K_La with liquid depth.

Tank geometry—header and diffuser location. In a full-size aeration tank, the aeration device location and the resulting flow patterns are important factors. For surface mechanical aeration devices that are usually evenly distributed over the surface area, the distance between aerators and the presence of draft tubes can cause overall mass transfer rate to vary significantly.[19] For diffused aeration, the effects of diffuser layout and flow pattern can have a significant effect on transfer efficiency; spreading out the diffusers over the tank floor improves oxygen transfer efficiency by as much as 74%.[10,20]

Variations in alpha factors of mixed liquor can be explained in terms of microbial oxygen uptake rate, an easily measured variable.

Bewtra and Nicholas[21] investigated the effect of tank widths, and concluded that reducing tank size from 7.3 m × 1.2 m (24 ft × 4 ft) to 2.4 m × 1.2 m (8 ft × 4 ft) at a 4.4 m (14.4 ft) water depth changed the mixing pattern from a spiral flow to "column aeration." This increased oxygen transfer efficiency 40 and 60% for coarse- and fine-bubble diffusers, respectively. The researchers stated that the reduced surface area had a "stilling effect," which reduced vertical liquid velocity and increased bubble retention time.

In the case of a single or double header, diffuser placement in a narrow or wide band also has an effect. Bewtra and Nicholas[21] noted higher oxygen transfer efficiency with a wide band than with a narrow band on a centerline header; Eckenfelder and Barnhart[22] did not detect any significant difference between these two types mounted at the tank side. According to Bewtra and Nicholas,[21] this may be because the aeration zone can be spread out at the center with wide band, while it is pushed to the wall with diffusers located at the tank side regardless of band type. Other studies on various diffusers and placement patterns have reported similar results.[2,23]

Water quality. The last important variable that affects mass transfer rate is water quality, which includes the presence and concentration of surfactants such as detergents, dissolved solids, and possibly suspended solids. Changes in bubble shape and size occur when the water is contaminated with surfactants. When a newly formed clean bubble rises through a liquid containing surfactants, the surfactant molecules adsorb to the bubble surface; the molecules are transported to the rear of the bubble and ac-

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cumulate there to form a "cap." A surface tension gradient, which opposes the tangential shear stress, reduces surface flow over the rear portion of the bubble surface. This cap grows with increasing surfactant concentration until it reaches the maximum size that the surface tension gradient can support.[24] The adsorbed molecules make the bubble more rigid and spherical[25] and reduce the surface renewal rate of air-water interface. As a result, the alpha value in the presence of surfactants is almost always less than unity in a diffused aeration system. The effect of a cap is most significant when the bubble motion is either spiral or zig-zag,[26] which occurs in the fine-bubble aeration systems. This is one reason that fine-bubble diffusers often have reduced alpha values in comparison to other types of diffusers.

Researchers have reported a wide range of alpha factors. Holroyd and Parker[27] reported alpha values of 0.63, 0.54, and 0.41 for 50 mg/L of the anionic British surfactants Teepol, Lissapol, and Turkey Red Oil, respectively, in a bench-scale diffused aeration, and 0.83, 0.93 and 0.85, respectively, with a 30-cm diameter disk surface aerator. Baars[25] reported that 10 mg/L of alkylaryl sulphonate, alkyl sulfate, and Lissapol reduced oxygenation capacity to 56.6, 53.3, and 42.6%, respectively, of that in tap water in bench-scale experiments with a dome diffuser. Stenstrom and Hwang[9] showed that alpha varied with 1.85 power of the ratio of surface tension in surfactant solution and tap water between 0.75 and 1.0 to the ratio, using a laboratory-scale diffused aeration system. Carver[28,29] reported that 50 mg/L of synthetic detergent reduced oxygen transfer rate by 60% for rising air bubbles and 50% for falling water droplets. Poon and Campbell[30] reported that soluble starch and glucose reduced alpha to 0.7 at 400 mg/L; peptone and nutrient broth gave an alpha value of approximately 0.5 at 1000 mg/L, while 4000 mg/L of sodium chloride had almost no effect on alpha value. All measurements were made with a fritted glass diffuser in a 0.14 m × 2.1 m (5.5 in. × 7 ft) water column.

The alpha factor is also affected by solids concentration. Baker *et al.*[31] reported that the alpha factor decreased from 0.9 to 0.4 when total solids concentration of poultry waste was increased from 1 to 5.5% in an oxidation ditch using cage rotors. Downing[32] found only a slight increase in K_La as suspended solids concentration increased from 2000 to 7000 mg/L; Lister and Boon[33] reported no variation of K_La in the same range. Holroyd and Parker[27] reported essentially no effect on K_La values with the addition of bentonite, a highly colloidal clay, using bench-scale diffused aeration devices. Casey and Karmo[34] obtained similar results with coarse and fine dried peat granules and PVC granules in concentrations up to 10 g/L, from laboratory-scale experiments on surface aeration. However, they also reported that the alpha factor varied from 0.84 to 1.2 with 0 to 12.5 g/L activated sludge. Jackson and Hoech[12] reported that a 0.69 alpha value for wastewater containing 600 mg/L ground wood pulp increased to 0.72 after filter paper was used.

These reports indicate that the alpha factor depends primarily on dissolved solids rather than on total or suspended solids concentration. The minor differences found by some researchers might be attributed to experimental variability. Many of the researchers did not actually measure power input for the mechanical aerators, which can change when surfactants or suspended solids are added.

Most researchers, however, have reported that alpha factors increased as treatment was increased. Downing *et al.*[18] and Wheatland and Boon[35] reported a linear dependence of alpha value on the amount of oxygen consumed by the microorganisms in a plug-flow aeration basin. Indeed, the results reported by Redmon and Boyle,[36] which showed that alpha increased from 0.35 to 0.6 as determined by the off-gas method in the full-scale, fine-bubble diffused aeration facility at Whittier Narrows, are typical of the trends noted by most researchers.

METHODS AND MATERIALS

Experimental facility. The experimental facility for diffused aeration column tests was assembled in the Whittier Narrows Wastewater Reclamation Plant of Los Angeles County Sanitation Districts (LACSD). The U. S. Environmental Protection Agency selected this test site to evaluate high efficiency transfer systems under process conditions. The plant receives a relatively constant flow of domestic wastewater from the main trunk sewers that flow to the Joint Water Pollution Control Plant of LACSD in Carson, Calif. Industrial inputs are minimized at this plant because the effluent is used for groundwater recharge. Three long, narrow aeration tanks of 9.1 m × 91 m × 4.9 m (30 ft × 300 ft × 16 ft) were equipped with the different types of diffusers. At the time of this experiment, the first tank was equipped with fine-bubble plate diffusers, the second with fine-bubble tube diffusers, and the third with jet aerators. The plate diffusers in Tank 1 were installed in a full-floor configuration and the tube diffusers in Tank 2 were installed near both side walls to create a cross-roll. Both diffusers were installed in a tapered aeration mode with approximately 45, 35, and 20% of the total number of diffusers in each one-third of the tank.

To determine alpha factors an aeration column (0.5-m I.D. PVC pipe, 4.8 m long) was placed adjacent to the aeration tank containing the plate diffusers. Taps were drilled at 0.6-m (2-ft) intervals along the column for sampling. A 17.7-cm (7-in.) diameter fine-bubble diffuser plate, was mounted on 1.27 cm (½ in.) PVC pipe and supported by two horizontal bars, and placed 0.6 m (2 ft) above the column bottom, which was the same height as in the full-scale aeration tank. Figure 1 shows the experimental set-up.

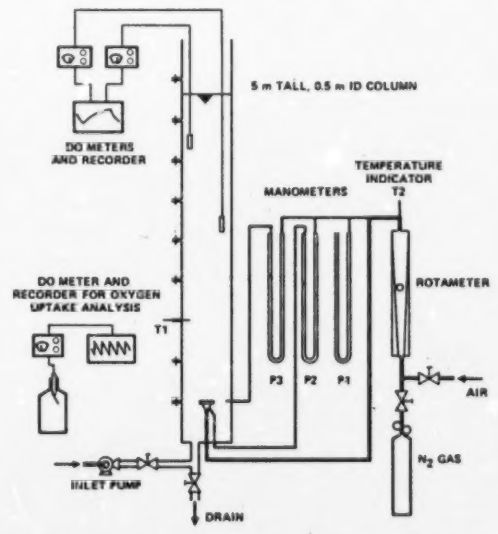

Figure 1—Experimental set-up for the diffused aeration column.

Dissolved oxygen (DO) concentration was measured by submerging two DO probes through the top of the column. Two DO meters and a continuous strip chart recorder were used to record DO concentration versus time. To measure the microbial oxygen uptake rate for the mixed-liquor tests, an additional DO probe and meter were connected to a recording digital voltmeter that recorded DO data in 30-second intervals. The Winkler procedure was used for measuring DO saturation concentration and for probe calibration. Nitrogen gas was used for deoxygenation by sparging it through the diffuser. Temperature was measured with a mercury thermometer in the early series of experiments and later with thermocouples and D.C. voltmeters.

Two rotameters, three U-tube manometers, and valves were mounted on a vertical panel and set beside the column. The measured air flow rate under the experimental conditions was corrected for pressure, moisture content, and temperature. The pressure drop across the orifice in the diffuser unit was converted to standard conditions and used as a second indicator of air flow rate.

Because a small quantity of trace contaminants can greatly influence the volumetric mass transfer coefficient, the experimental column was carefully cleaned before a series of clean water tests were performed. Another series of tests followed, using clean water plus dodecyl sodium sulfate, an anionic surfactant. Next mixed liquor was tested. The measurements were taken between 4.5 and 7.5 m (15 and 25 ft) from the inlet end of the aeration tank to ensure primary effluent was mixed thoroughly with return sludge. The initial oxygen uptake rate was 40 to 70 mg/L · h. A maximum of seven experiments were performed with each batch of mixed liquor.

Mathematical models. For clean water tests, a nonsteady-state adaptation of the two-film theory is usually used in a batch reactor, so that the oxygen mass balance on the liquid side is expressed as

$$\frac{dC}{dt} = K_L a(C_\infty^* - C) \tag{1}$$

where

$K_L a$ = volumetric mass transfer coefficient,
C = saturation DO concentration, and
C_0 = DO concentration in liquid.

This can be integrated to

$$C = C_\infty^* - (C_\infty^* - C_0)e^{-K_L at} \tag{2}$$

where

C_0 = initial DO concentration in liquid.

For dirty water tests, a steady- or nonsteady-state test method can be used in either a batch or continuous-flow reactor. The oxygen mass balance equation includes the oxygen consumption by microorganisms and DO content in influent and effluent streams:

$$\frac{dC}{dt} = K_L a(C_\infty^* - C) - R(t) - \frac{Q}{V}(C - C_i) \tag{3}$$

where

$R(t)$ = microbial oxygen uptake rate,
Q = mixed-liquor flow rate,
V = liquid volume in the reactor, and
C_i = DO concentration in influent.

When the microbial oxygen uptake rate can be assumed constant during the experiment, Equation 3 can be integrated:

$$C = C'_R - (C'_R - C_0)e^{-K_L a' t} \tag{4}$$

where

$$K_L a' = K_L a + \frac{Q}{V}, \text{ and} \tag{5}$$

$$C'_R = \frac{K_L a}{K_L a'} - \frac{1}{K_L a'}\left(R_c - \frac{Q}{V}C_i\right). \tag{6}$$

In a batch reactor, the continuity terms in Equation 3 are zero and the variables $K_L a'$, C'_R in Equation 4 are replaced with $K_L a$ and C_R:

$$C = C_R - (C_R - C_0)e^{-K_L at} \tag{7}$$

and

$$C_R = C_\infty^* - \frac{R_c}{K_L a} \tag{8}$$

If the microbial oxygen uptake rate changes with time, Equation 3 is not readily solvable unless the form of the varying oxygen uptake rate can be expressed as a linear function of time. In a batch reaction mode this is possible if the microbial oxygen uptake rate term is expressed as

$$R(t) = a_1 L(t) + b_1 S(t) \tag{9}$$

where

$L(t)$ = substrate concentration,
$S(t)$ = mixed liquor suspended solids (MLSS) concentration, and
a_1, b_1 = constants.

$a_1 L(t)$ represents the oxygen consumption caused by substrate metabolism, and $b_1 S(t)$, the oxygen consumption caused by endogenous respiration. The variation of microbial solids concentration can be ignored when compared to the variation of substrate over the period of an aeration test so that $b_1 S(t)$ can be replaced by a constant, R_c.

$$R(t) = a_1 L(t) + R_c \tag{10}$$

If the rate of biological oxidation of substrate can be assumed to be first-order, then:

$$\frac{dL(t)}{dt} = -K_u L(t) \tag{11}$$

Integrating Equation 11 and substituting into Equation 9, this form is obtained:

$$R(t) = R_0 e^{-K_u t} + R_c \tag{12}$$

Substitution of Equation 12 into Equation 3 and solving for C in batch mode gives

$$C = C_R - \left(C_R - C_0 - \frac{R_0}{K_L a - K_u}\right)e^{-K_L at} - \frac{R_0}{K_L a - K_u}e^{-K_u t} \tag{13}$$

In this expression, the volumetric mass transfer coefficient is assumed constant during the test period; however, when the water quality changes rapidly, such as in the batch reactor filled with fresh mixed liquor, the constant mass transfer rate assumption can result in significant errors in estimating $K_L a$

and C^*_∞. To allow for changing mass transfer coefficients, a linear dependency of the mass transfer coefficient on dissolved solids or substrate concentration can be assumed over a small range of variation:

$$K_La = a_3L(t) + b_3 \quad (14)$$

By combining Equations 10 and 14, the volumetric mass transfer coefficient can be expressed as

$$K_La = a_4R(t) + b_4 \quad (15)$$

Substitution of Equation 15 into Equation 3 and dropping the flow term for batch mode, the mass balance equation becomes

$$\frac{dC}{dt} = (a_4R(t) + b_4)(C^*_\infty - C) - R(t) \quad (16)$$

with $R(t)$ given by Equation 12. By performing a series of experiments, the relationship between the volumetric mass transfer coefficient and microbial oxygen uptake rate can be established.

Parameter estimation. The parameters, K_La, C^*_∞, and C_0 in Equation 2 can be estimated by any of several nonlinear parameter estimation techniques, such as the linearization method or Box search method.[4,37] In the case of constant K_La in a continuous-flow reactor, the parameters K_La', C', and C_0 in Equation 4 and K_La and C^*_∞ can be obtained from Equations 5 and 6 respectively, and in a batch reactor, K_La, C_R, and C_0 are derived from Equation 7 and C^*_∞ from Equation 8. These parameters can be estimated using the computer code in the American Society of Civil Engineers (ASCE) Standard Oxygen Transfer Procedure.[38]

If microbial oxygen uptake rate is assumed to decrease exponentially, but the volumetric mass transfer coefficient is assumed constant, the values of K_La, C_R, and C_0 are estimated from Equation 13, using the linearization method although new sets of derivatives for the computer code are required for Equations 2, 4, 7, and 13.[39] The same algorithm can be used to estimate R_0 and R_c in Equation 12 from microbial uptake rate versus time data in a batch reactor with a slight modification.

If the volumetric mass transfer coefficient is assumed to vary with time, a_4, b_4, C^*_∞ and C_0 can be estimated from Equation 16 with a search method, such as the Box method, and a numerical integration technique to solve the differential equations. Although any convenient technique can be used, the Continuous Systems Modeling Program[40] was used in this work.

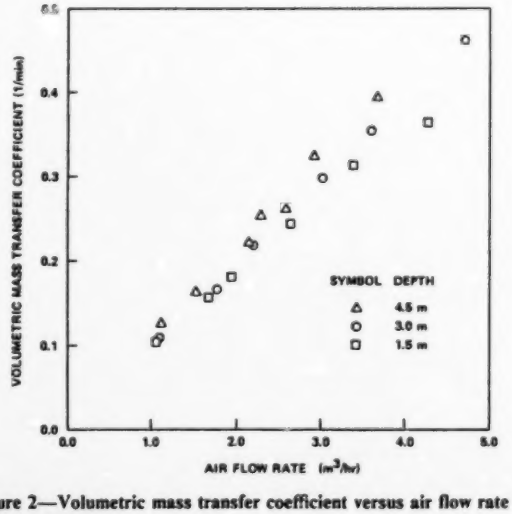

Figure 2—Volumetric mass transfer coefficient versus air flow rate for different depths.

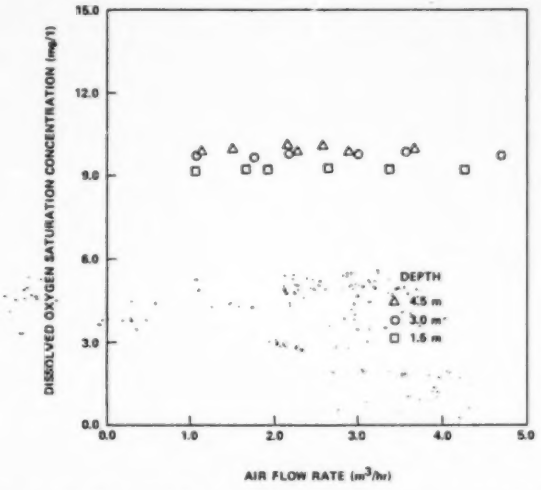

Figure 3—Saturation DO concentration for tap water versus air flow rate for different depths.

RESULTS AND DISCUSSION

Clean water results. The experiments covered a 1.5 to 4.3 m (5 to 14 ft, 2 in.) water depth, and a 1.02 to 4.76 m^3/h (0.6 to 2.8 scfm) air flow rate. The water temperature varied from 25 to 30°C. Volumetric mass transfer coefficients under process conditions were converted to standard condition using the ASCE recommended theta value of 1.024.[38] The data show a linear dependence of volumetric mass transfer coefficient on air flow rate at each water depth.

The volumetric mass transfer coefficients versus air flow rate are plotted in Figure 2 for each water depth. K_La generally increased with depth as liquid depth changed from 1.5 m (5 ft) to 4.3 m (14 ft, 2 in.); this trend contrasts with previous findings. Jackson and Shen[11] reported that K_La changed with −0.45 to −0.55 power of liquid depth. Yunt,[41] Bacon *et al.*,[3] and Urza and Jackson[7] also reported slight decreases of K_La with liquid depth. However, in all cases the diffusers were located at or very close to the tank bottom. In this research, the diffuser was lifted 0.6 m (2 ft) above the column bottom, and the "dead zone," which was as much as 40% of the total column volume at a 1.5-m (5-ft) water depth, could have caused this difference. In other test results not shown in Figure 2, K_La increased slightly as the liquid depth increased to 4.6 m (15 ft).

Figure 3 shows the saturation DO concentration at three water depths. There was no significant variation of saturation concentration with air flow rate. Standard error values at each depth were less than 1.0 mg/L. The value increased with water depth, as shown in Figure 4. The extrapolated value at zero water depth of 9.06 mg/L is close to surface saturation concentration at standard conditions.[42]

Surfactant results. The summary of experimental results is presented in Table 1. As seen in Runs 32 to 39, the replication of volumetric mass transfer rate was excellent with a standard

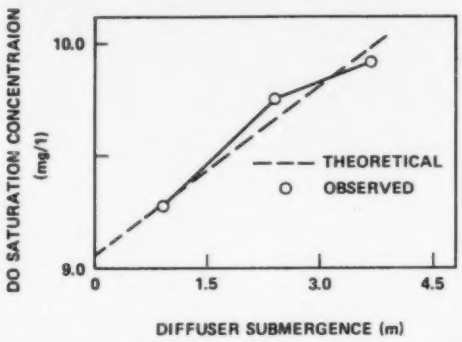

Figure 4—DO saturation concentration versus diffuser submergence.

error of 3.5% in each batch of test liquid; however, the results using two different grades of dodecyl sodium sulfate (DSS) from two different manufacturers differ considerably. In the first 2 days, 15 mg/L technical grade DSS from the first manufacturer was used for Runs 32 through 34 and 5 mg/L DSS for Runs 35 and 36. This chemical was stripped easily from the liquid with rising air bubbles, so that the surface tension rapidly increased and approached the value for tap water. In the remaining experiments, 5 mg/L of reagent grade DSS from the second manufacturer was used. This chemical had been successfully used in a long series of experiments in the UCLA Water Quality Laboratory.[43]

The variation may be partially caused by the mixing technique of concentrated DSS solution with column contents. In the early experiments with DSS solution, a 2-L concentrated solution was mixed with water from the top of the aeration column. This concentrated solution of 2.19 g/L was close to the critical micelle concentration, which is 2.48 g/L at 40°C.[45] Consequently, the surfactant molecules at the high concentration in the top section of the column might have exceeded the critical micelle concentration, allowing the micelles to be rejected before they were mixed with water in the lower portion of the column. The surfactant, once stripped and condensed at the surface, remained a stable foam and was not mixed into the water again. In the later series, the concentrated solution was added slowly and continuously as the column was filled. The foams in this series were broken down continuously with a spray of water from the top, so that a relatively uniform distribution of detergent was possible. The difference in the chemical variation from the two manufacturers may not have been entirely responsible for the results.

Trends in alpha factor variation with air flow rate are shown in the data. The alpha factor generally decreased with increasing gas flow rate and depth. The alpha factor ranged from a low 0.35 at 4.3 m depth at 3.72 m^3/h (2.19 scfm), to a high 0.85 at 1.5 m depth and 1.39 m^3/h (0.82 scfm). The lowest air flow rate in each batch was tested last, but the results of Runs 32 through 39 showed no significant chronological trend.

The volumetric mass transfer coefficient or alpha value in Runs 132 to 140 were much higher than the earlier test results. The later experiments were conducted after mixed liquor testing, when residue on the wall of PVC column was difficult to remove and some may have remained. The surfactant in the later tests might have adsorbed to the residue on the wall, so that the solution surfactant concentration was less. A higher initial surfactant concentration might have overcome these variations.

Mixed liquor test results. For the mixed liquor test in the column, three nonsteady-state experimental techniques were used: constant oxygen uptake rate (OUR), batch test; decaying OUR, batch test; constant OUR, continuous-flow test.

Constant OUR nonsteady-state batch test. During this test series the aeration column was filled over a 2-hour period to the 4.3-m liquid depth. When pumping began the mixed liquor depth in the column increased rapidly because of the hydraulic head from the aeration tank, and the rising speed of liquid depth slowed as the liquid depth increased. During this pumping period, air flow rate was kept high so that DO concentration in the liquid column was 3 mg/L or more. Preliminary studies of fresh mixed liquor samples showed that the initial high OUR decreased in 1.5 hours to assume a relatively constant value. The time required to fill the column ensured that all the tests in this series would take place during the endogenous phase. Uptake rate versus time is shown in Figure 5.

In the first series of experiments, microbial OUR did not change more than 10% during each test because microbial growth was always in the endogenous phase. The volumetric mass transfer coefficients are presented as a function of air flow rate in mixed liquor in Figure 6. Unlike tap water, K_La values in mixed liquor were slightly greater at lower water depth.

Decaying OUR nonsteady-state batch test. The second set of experiments used a new pump that filled the aeration column to the 4.3 m depth in less than 7 minutes. Mixed-liquor was taken from the 4.6 m length of Tank 1. Both measures were

Table 1—Summary of detergent test results.

Experiment number	Date	Water depth (ft)	Air flow rate (SCFM)	K_La_{20} (min^{-1})	$C_{\infty 20}^*$ (mg/L)
32	9/15/81	14.3	1.66	0.139	10.4
33		14.3	1.67	0.132	10.6
34		14.3	1.68	0.142	10.5
35	9/16/81	14.3	2.22	0.208	10.1
36		14.3	2.22	0.229	9.8
37	9/17/81	14.3	2.23	0.286	10.1
38		14.3	2.24	0.292	9.8
39		14.3	2.24	0.277	9.9
40	9/22/81	14.2	2.23	0.152	10.1
41		14.2	1.38	0.103	9.8
42		14.2	0.69	0.050	9.5
43	9/23/81	10.0	2.14	0.125	9.3
44		10.0	1.34	0.095	9.3
45		10.0	0.66	0.051	9.1
46	9/24/81	5.0	2.08	0.128	8.7
47		5.0	1.26	0.094	8.8
132	5/6/82	14.3	2.20	0.244	10.2
133		14.4	1.71	0.180	10.0
134		14.3	0.90	0.113	9.7
135	5/6/82	10.0	2.16	0.263	10.4
136		10.0	1.62	0.225	9.2
137	5/7/82	10.0	0.89	0.130	9.4
138	5/7/82	5.0	2.09	0.21	9.2
139		5.0	1.54	0.181	9.1
140		5.0	0.82	0.113	8.8

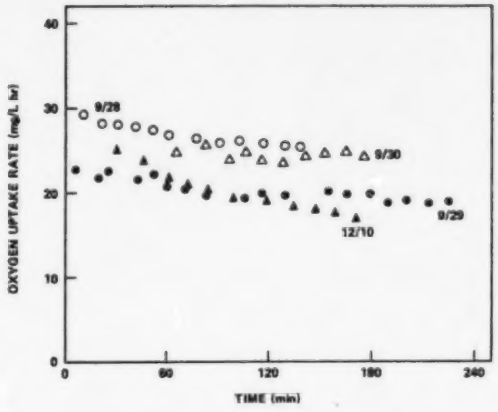

Figure 5—Oxygen uptake rates during constant OUR tests.

designed to ensure that the initial high OUR that occurred in the aeration tank also occurred in the aeration column. Figure 7 shows a typical response of OUR in the rapidly-filled aeration column. Uptake rate was 60 to 70 mg/L · h at the sampling point in the aeration tank and decreased exponentially to 18 to 22 mg/L · h in about 2 hours.

Volumetric mass transfer coefficients versus microbial OURs are shown in Figure 8 for the 4.3 m mixed liquor depth. The average air flow rate of these nine experiments was 3.91 m^3/h (2.30 scfm) with a standard deviation of 0.073 m^3/h (0.043 scfm). Each line represents a single experiment. A range of K_La values was obtained, because the varying K_La procedure (Equation 16) was used. Except for one experiment, all results fell in one line, which shows good linear dependency of volumetric mass transfer coefficient on microbial OUR.

The range of experiments for rapidly decaying OUR covered all three liquid depths and at least three air flow rates in each liquid depth and OURs from 20 to 65 mg/L · h.

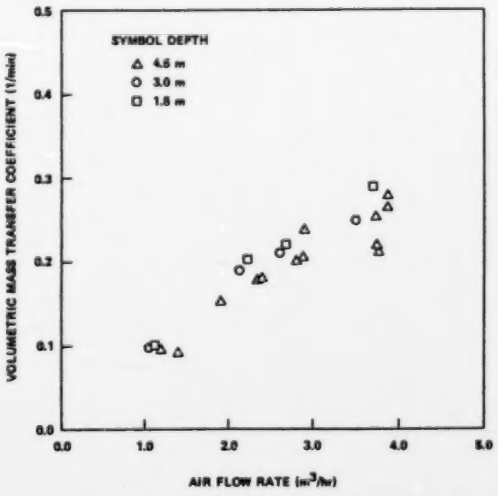

Figure 6—Mass transfer coefficient versus air flow rate in mixed liquor.

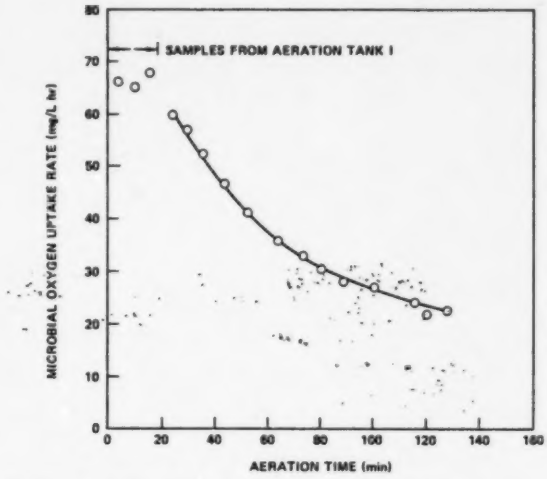

Figure 7—Oxygen uptake rate (mg/L · h) versus time (min).

Constant OUR nonsteady-state continuous-flow test. The purpose of the last series of experiments was to check the variation of volumetric mass transfer coefficient at higher uptake rate than could be obtained with the nonsteady-state batch test. Only two experiments were conducted in continuous-flow mode. After the aeration column was filled with a new batch of mixed liquor (in about 7 minutes), mixed liquor was continuously pumped into the aeration column to keep a high OUR. The results of the continuous tests should equal the results from the batch test, extrapolated to the initial value of OUR. The summary of experimental results is shown in Table 3.

DISCUSSION

Figures 9 through 11 show the experimental results in mixed liquor at liquid depths of 4.3 m (14 ft, 2 in.), 3 m (10 ft) and

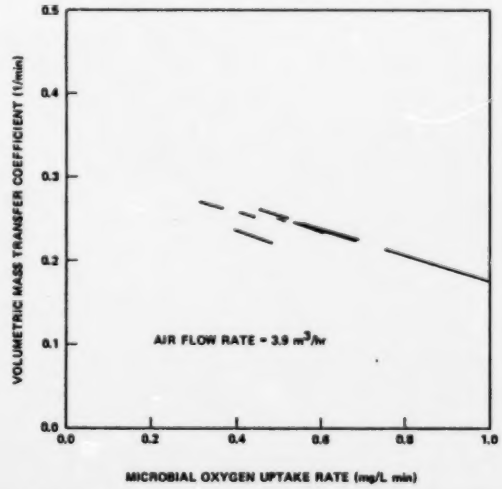

Figure 8—Mass transfer coefficient versus oxygen uptake rate in decaying OUR tests.

Table 2—Summary of steady state continuous flow test.

MLSS flow rate (gal/min)	MLSS volume (gal)	Air flow rate (SCFM)	O_2 uptake rate (mg/L · h)	K_La_{20} (a/min)	C_∞* (mg/L)
14.0	230	2.24	41.0	0.222	9.6
14.0	230	2.25	39.5	0.211	9.8

1.5 m (5 ft). Short solid lines on the figures represent results of nonsteady-state tests with changing volumetric mass transfer rate with OUR during each experiment. Individual points represent constant OUR experiments, while the long solid lines are best fits of all results at each gas flow rate. The line length of each nonsteady state test shows the change of microbial OUR during the test. Figure 12 shows the variation of alpha in 4.3 m mixed-liquor depth with air flow rates. As the air flow rate increased, alpha decreased. At 24 mg/L · h OUR, the alpha value changed from 0.73 to 0.64 as air flow rate increased from 0.36 to 1.14 m/s (0.72 to 2.28 scfm).

The alpha factor was also affected strongly by liquid depth. Figure 13 shows the alpha factor as a function of water depth at two different flow rates and three OUR values. The value at zero OUR is an extrapolation of the results shown in Figure 9. The alpha factor, as expected, was lowest at the highest OUR. The alpha factor decreased with increasing depth and flow rate, similar to the results found in the surfactant tests.

Although it was hoped that an OUR could have been obtained in the column that approximated the tank OUR, the continuous-flow tests proved unsuccessful. The alpha factors derived from continuous-flow tests more closely resembled endogenous alpha factors than high-OUR alpha factors.

Comparison with full-scale systems. The diffuser used in this research was the same type used by Yunt at LACSD in two separate studies of full-scale systems.[41,45] Two data sets are analyzed for comparison. The first data set is from one of Yunt's experiments using tap water in Grid 1 of Tank 1 at the Whittier Narrows plant. Water depth was 4.5 m (14.84 ft) and the diffusers were mounted 0.6 m (2 ft) above the tank bottom. The 724 diffusers were arranged in a 9.1 m × 91 m (30 ft × 100 ft) floor pattern to give 0.38 m^2 (4.1 sq ft) per unit diffuser. The second set of data is from the rectangular tank of 6.1 m × 6.1 m × 7.6 m at the Joint Water Pollution Control Plant in Carson, Calif. Ninety-eight diffusers were installed, so that the floor area per unit diffuser was approximately the same as in the first data set.

These two data sets are plotted in Figure 14 as K_La versus superficial air flow velocity. Superficial air flow velocity is calculated by dividing the flow per diffuser by the unit area per diffuser. The dashed line in Figure 14 shows the column results, For both data sets, the K_La values are about 20% higher in the tank than in the aeration column. This difference is believed to be the result of column wall effects that change the mixing pat-

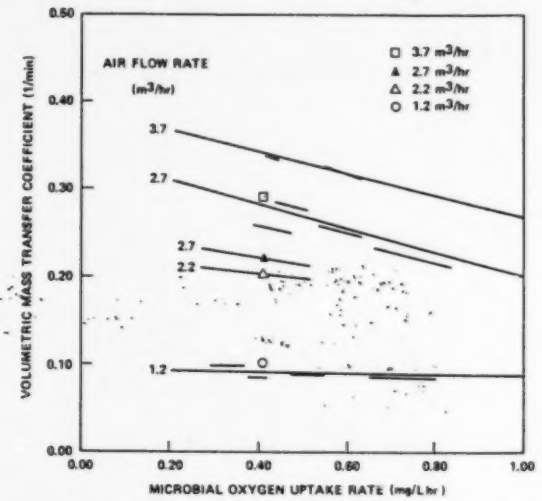

Figure 10—Mass transfer coefficient versus oxygen uptake rate (at 3 m).

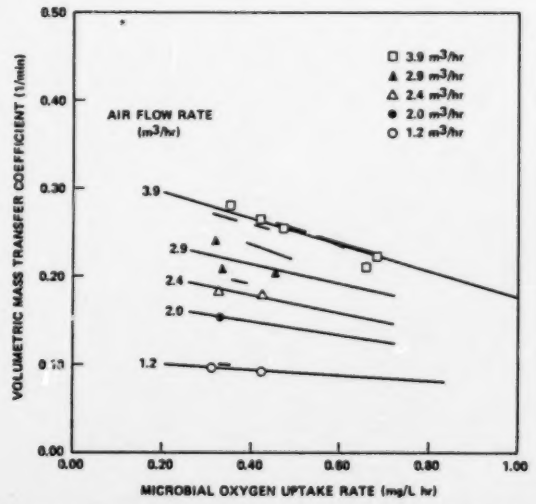

Figure 9—Mass transfer coefficient versus oxygen uptake rate (at 4.3 m).

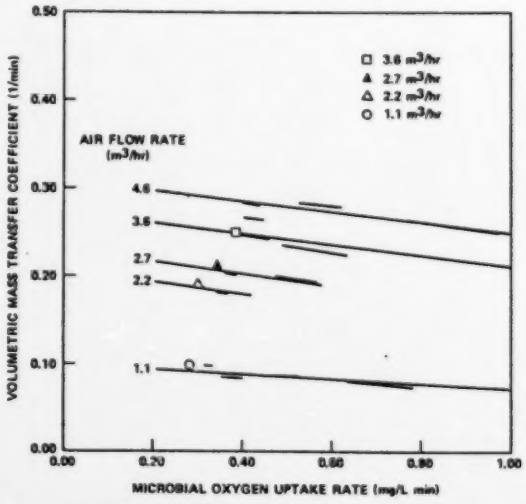

Figure 11—Mass transfer coefficient versus oxygen uptake rate (at 1.5 m).

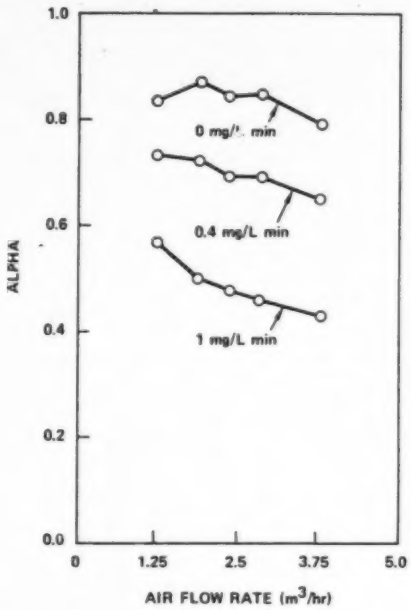

Figure 12—Alpha factor versus air flow rate at 4.3 m.

tern, bubble rising velocity, and bubble entrapment. Figure 14 shows a constant and reproducible offset in K_La values from the column and full-scale tank. By ratioing the values obtained in the column to their equivalent value in the aeration tank, and by using the appropriate alpha values (or dirty water K_La value), it can be shown that the column performance closely predicts the full-scale performance, as measured by full-scale mixed liquor tests.

The results from the clean water testing can be compared to the mixed liquor tests conducted in Tank 1 at Whittier Narrows by Mueller[46] and by the authors in the summer of 1981. The dual nonsteady-state and the steady-state technique were used.

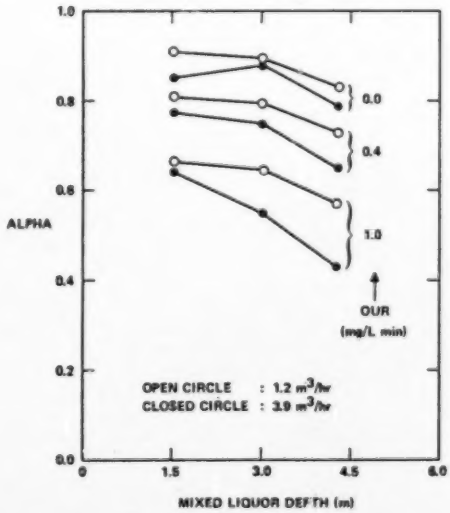

Figure 13—Alpha factor versus mixed liquor depth.

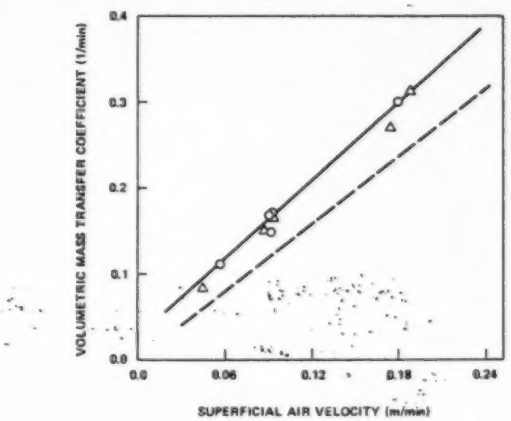

Figure 14—Mass transfer coefficient versus superficial air flow rate in clean water.

These tests were performed in Grids 2 and 3 where floor area per unit diffuser were 0.47 and 0.79 m^2 (5.05 and 8.52 ft^2), respectively.

The following procedure was used to compare the column and mixed liquor test results:

1. Read the K_La value for a given OUR and air flow rate from Figure 9.
2. Convert the K_La value to that at field condition according to floor area per unit diffuser.
3. Apply geometric conversion factor (defined as the ratio of K_La value in clean water in aeration column to the one in full-scale tank. This corrects for the column wall effects).

Figure 15 shows the comparison of full-scale test results and extrapolated results from the column.

Surface tension. Secondary oxygen transfer parameters, such as OUR, can be useful to determine or control oxygen transfer at treatment plants. Surface tension is another candidate parameter. Surface tension was measured at various times during this

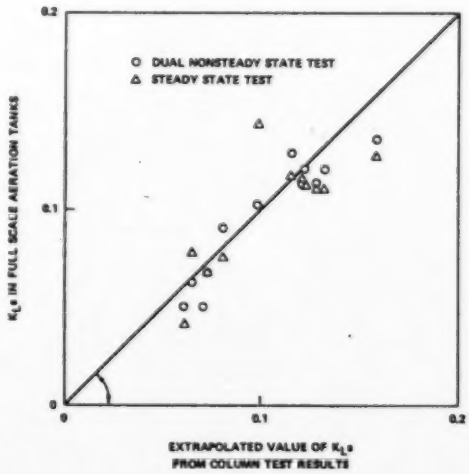

Figure 15—Comparison of column and full size tank test results.

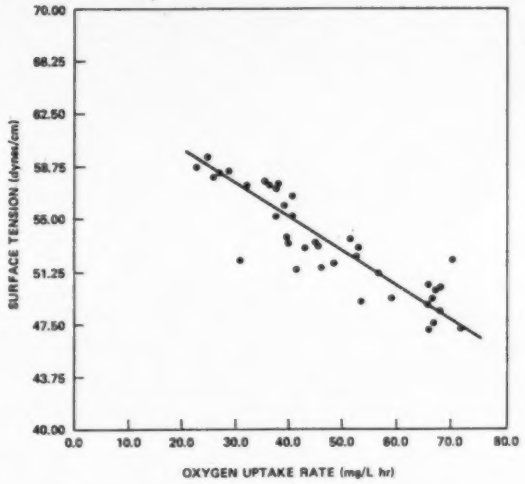

Figure 16—Surface tension versus oxygen uptake rate.

study, using the Du Nouy ring method[44] to determine whether there was a relationship between alpha factors and surface tension. Unfortunately, insufficient data was collected to correlate a relationship; however, a correlation of OUR and surface tension was made, and its results are shown in Figure 16. Surface tension might, therefore, be used as an indicator of alpha factors or transfer efficiency.

SUMMARY

In this research, oxygen transfer using fine-bubble diffusers in the presence of wastewater contaminants and surfactants was studied. Based on mathematical development and experimental work, the primary objective was achieved. An experimental method and mathematical models that can handle rapidly changing water quality under process conditions have been developed, along with suitable methods for parameter estimation. The models were verified experimentally with both tap water containing surfactants and activated sludge mixed liquor. It was shown that the pilot-scale aeration column with full-scale liquid depth under operating condition could be used to simulate the full-scale aeration tank. The variation of alpha factor in the mixed liquor can be explained by a readily measured variable, microbial oxygen uptake.

Alpha factors decreased with increasing air flow rate and diffuser submergence, in all cases, for both mixed liquor and tap water containing surfactant. A plausible mechanism to explain this trend in alpha factors is bubble coalescence. As gas flow rate and depth increase, there is more opportunity for bubble collisions and coalescence, which would result in larger bubbles with less specific surface area. Surfactants are known to change the coalescence properties of liquids. If this relationship is true, then greater diffuser spacing might increase alpha factors.

CONCLUSIONS

- The alpha factor in detergent water for fine-bubble diffusers varied between 0.35 to 0.8, with the same concentration of surfactant.
- Microbial OUR in mixed-liquor explained the variation of volumetric oxygen mass transfer coefficient in mixed-liquor. As the water was treated, soluble substrate was removed and microbial oxygen uptake rate decreased to the value of endogenous phase, and the volumetric oxygen mass transfer coefficient increased. It was shown that the variation of volumetric oxygen mass transfer coefficient can be related linearly to microbial OUR. This relationship should be site-specific for each installation.
- Alpha factors in mixed liquor increased significantly with increasing treatment. The practice of measuring endogenous alpha factors for this plant would have resulted in an alpha value much greater than the true alpha in the aeration tank.
- Alpha factors in tap water containing surfactant and mixed liquor decreased with increasing air flow rate.
- Alpha factors in mixed liquor decreased with increasing liquid depth.
- For this study, the volumetric mass transfer coefficient was linearly dependent on air flow rate, in contrast with results of other studies. This difference may be attributed to the height of the diffuser above the tank floor.

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